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Tribological Behavior of Metal Matrix Composites

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The wear and friction behavior of continuous graphite-fiber-reinforced metal matrix composites was investigated. Composite materials were tested against 4620 steel at 54 m/sec at room temperature in air without lubricant. The graphite fibers studied included rayon-based, pitch-based, and polyacrilonitrile (PAN)-based fibers. Both high-modulus and high-strength PAN-based fibers were examined. The fibers were incorporated into Cu- and Ag-based alloys by means of a liquid metal infiltration technique. The results of this study indicate that the type of graphite fiber in the composite is the most

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significant factor in the wear and friction behavior of metal matrix composites. In some high-modulus fiber Sn-bronze composites fiber fraction influences wear rate, but not coefficient of friction. Neither the matrix alloy nor the composite tensile strength per se correlates with the friction and wear properties; however, there are specific trends for the various matrix alloys.

CONTENTS

FIGURES

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TABLES

INTRODUCTION

Recent studies indicate that the wear and friction behavior of graphite fiber-metal matrix composites can be substantially better than that of the unreinforced matrix material [1-4]. The wear rates of bronze matrix composites decrease with increasing Sn content, thus reflecting the contribution of matrix hardness to wear resistance. Fiber orientation also has a significant effect on wear; the best wear resistance occurs when the fiber ends are normal to the sliding surface. This orientation prevents the fibers from being plucked from the surface during sliding.

Metal matrix composites that contain low-modulus polyacrilonitrile (PAN)-based graphite fibers have a lower wear rate than those containing high-modulus rayon-based or PAN-based graphite fibers. The wear rates of the various composites are related to the size of the debris particles generated during sliding, which correlates with the grain size of the constitutent graphite fiber.

The wear and friction behavior of metal matrix composites is also a function of sliding speed. The sliding speed that results in minimum wear is determined by the rate of oxide formation and surface destruction caused by the softening of the matrix.

In the previous studies the conclusions were derived on the basis of only one type each of low-modulus PAN-based, high-modulus PAN-based, and rayon-based graphite fibers. In this study several different fibers were examined, which included a high-modulus pitch-based fiber and additional high-modulus PAN-based and low-modulus PAN-based fibers.

The fiber fraction is expected to have a significant effect on the wear and friction behavior of the composites. Unfortunately, the liquid infiltration technique used in the processing of these composites is not amenable to controlled variation of fiber content over a wide range. A characteristic fiber fraction does occur for a specific fiber and matrix combination, and some additional variation is possible by process modifications. In this study the effect of intentionally produced and naturally occurring fiber fraction variation on wear and friction behavior was examined.

The matrix effects resulting from varying Sn content in bronze indicate that mechanical and chemical properties of the matrix should influence the wear behavior of metal matrix composites. In this study more matrix compositions including Cu and Ag alloys were examined than had been examined in the past.

EXPERIMENTAL PROCEDURES

The composite materials were processed by a method described elsewhere [2, 5]. The graphite fibers used in this study and some of the mechanical properties are given in Table I. Fibers not previously examined include the high-modulus Type I PAN-based fiber, Modmor I; high-strength Type II PAN-based fiber, Celion 6000; and pitch-based Thornel Type VSA-11. The properties of the composites fabricated and tested for this study are given in Table II. A number of composites tested in this study were fabricated previously, and their properties are to be found in a recent publication [2]. All alloys were prepared specifically for these composites except the Al-bronze (alloy 954) and the Cu-Ag-P-Mg alloys (SSC 115), which are commercially available. The tensile strengths of consolidated plates were determined from the flexural strength of four-point bend specimens. For those composites that were not processed in sufficient quantity to produce bend specimens, the strengths are based on tensile tests performed on precursor wire specimens by means of a technique previously described. These specimens were tested against 4620 steel at 54 m/sec sliding speed at room temperature in air without lubricant. The testing apparatus and details of the test procedure have been previously described [2]. The volume fractions of fiber given in Table II are those that would form naturally with minimum fiber tension under Ar atmosphere during infiltration. One material, Celion 6000/Cu-0.04Ag-0.05P-0.11Mg (SSC 155), was also infiltrated under an atmosphere consisting of 90Ar-10H to effect a greater fiber volume loading.

Table I. Properties of Graphite Fibers

Precursor	Commercial Designation	Fiber Diameter, μm	Tensile Strength, G Pa	Youngs Modulus, G Pa	Density, 10^3 kg m^{-3}
Rayon	Thornel 50	6	2.40	413	1.670
PAN	Hm 3000	7	2.43	365	1.904
	Modmor I	8	2.05	317	1.849
	Thornel 300	7	2.65	227	1.750
	Celion 6000	7	2.92	228	1.750
Pitch	VSA-11	11	1.20	380	1.990

Table II. Composite Materials

Fiber	Matrix	Fiber Volume, %	Tensile Strength	Density, 10^3 kg m^{-3}
Thornel 50	Cu-6Sn	42	538	5.827
	Cu-10Sn	34	a	6.360
HM 3000	Cu-6Sn	39	607	6.126
Modmor I	Cu-6Sn	35	662	6.424
Thornel 300	Cu-0.04Ag-05P-0.11M (SSC 155)	38	511[b]	6.186
	Cu-6Sn	44	331	5.755
	Cu-11Al-4Fe (954)	32	575[b]	5.745
	Ag-20Cu	44	324	6.474
	Ag-28Cu	42	384[b]	6.585
Celion 6000	Cu-0.04Ag-0.05P-0.11Mg (SSC-155)	42	539[b]	5.935
		52[c]	728[b]	5.880
	Cu-11 Al-4 Fe (954)	29	724[b]	5.880
	Ag-28Cu	40	459	6.794
	Ag-26Cu-2Ni	28	730[b]	7.652
VSA-11	Cu-0.04Ag + 0.05P+ 0.11 Mg (SSC 155)	33	403	6.589
	Ag-28Cu	38	338	6.794

[a] Not determined.

[b] Precursor wire properties

[c] Infiltrated under hydrogen containing atmosphere.

RESULTS AND DISCUSSION

The wear behavior of the metal matrix composites is summarized in Table III. The three fiber orientations studied are: fibers axis normal to sliding surface (I), fiber axis parallel to sliding surface but normal to the sliding direction (II), and fiber axis parallel to both sliding surface and direction (III). The wear rates are expressed in both the weight lossed per kilometer of sliding and the equivalent distance abraded away in the slider specimen with a uniform wear rate for the sliding surface assumed. This assumption does not always hold; therefore, weight-loss measurements were used in the graphical presentation of the data. The coefficient of friction values reported here are the averages obtained for each of the ten sliding cycles to which the specimens were subjected.

In the previous study [2] the friction and wear rates of composites of a high-modulus fiber, HM 3000, and a high-strength fiber, T 300, in a Cu-1Sn matrix were compared. The friction and wear rate was higher for the high-modulus fiber composite. The effect of the type of fiber was examined more extensively in this work for both bronze and Ag matrix composites. The wear and friction behavior for Orientation I fiber composites are shown in Figs. 1 and 2, respectively. The composites with high-modulus fibers appear to have wear rates that are noticeably larger than those with high-strength fibers. The variation in wear properties of the different high-modulus fiber composites is in constrast to the relatively similar behavior in the various high-strength composites. The difference in friction behavior also is evident between the high-strength and high-modulus fiber

Table III. Wear and Friction Behavior of Metal Matrix Composites

Composite	Fiber Fraction, %	Orientation[a]	Wear Rate, mg/km	Wear Rate, μm/km	Coefficient of Friction	Maximum Temperature, K
Thornel 50/Cu-6Sn	42	I	2.07	8.08	0.41	570
		II	6.24	24.16	0.42	652
		III	7.71	31.06	0.48	636
Thornel 50/Cu-10Sn	34	I	0.80	2.99	0.36	541
		II	1.43	5.42	0.50	552
		III	1.52	5.81	0.40	552
HM 3000/Cu-1Sn	32	I	1.01	3.77	0.47	573
		II	15.70	57.46	0.32	504
		III	10.42	38.27	0.41	505
HM 3000/Cu-3Sn	39	I	0.43	1.61	0.23	456
		II	2.47	9.28	0.37	512
		III	3.71	13.78	0.17	479
HM 3000/Cu-4Sn	35	I	1.10	4.79	0.19	467
		II	4.02	16.62	0.37	488
		III	4.27	19.96	0.41	520

Table III. Wear and Friction Behavior of Metal Matrix Composites (Continued)

Composite	Fiber Fraction, %	Orientation[a]	Wear Rate, mg/km	Wear Rate, μm/km	Coefficient of Friction	Maximum Temperature, K
HM 3000/Cu-6Sn	44	I	0.62	2.43	0.34	533
		II	1.69	6.68	0.51	543
		III	1.31	5.13	0.32	539
HM 3000/Cu-8Sn	36	I	0.52	1.96	0.30	396
		II	0.93	3.54	0.33	398
		III	1.45	5.57	0.37	390
Modmor I/Cu-6Sn	35	I	0.52	1.93	0.26	524
		II	1.68	6.24	0.31	578
		III	3.31	12.37	0.38	578
T 300/Cu-6Sn	44	I	0.13	0.64	0.10	446
		II	0.50	2.76	0.31	510
		III	0.39	2.08	0.19	488
T 300/Cu-Ag-P-Mg (SSC 155)	38	I	0.07	0.25	0.15	417
		II	0.39	1.16	0.23	456
		III	0.31	1.22	0.26	495

Table III. Wear and Friction Behavior of Metal Matrix Composites (Continued)

Composite	Fiber Fraction, %	Orientation[a]	Wear Rate, mg/km	Wear Rate, μm/km	Coefficient of Friction	Maximum Temperature, K
T 300/Cu-Al-Fe (954)	30	I	0.23	0.92	0.09	426
		II	0.43	1.87	0.14	477
		III	0.28	1.20	0.26	463
T 300/Ag-20Cu	40	I	0.13	0.60	0.12	433
		II	0.13	0.57	0.22	463
		III	0.14	0.64	0.09	478
T 300/Ag-28Cu	39	I	0.12	0.42	0.13	425
		II	0.14	0.57	0.17	437
		III	0.16	0.64	0.43	494
Celion 6000/Cu-Al-Fe (954)	38	I	0.09	0.36	0.07	389
		II	0.22	0.95	0.15	420
Celion 6000/Cu-Ag-P-Mg (SSC 155)	42	I	0.12	0.48	0.18	439
		II	0.21	0.85	0.21	453
		III	0.28	1.16	0.21	455

Table III. Wear and Friction Behavior of Metal Matrix Composites (Continued)

Composite	Fiber Fraction, %	Orientation[a]	Wear Rate, mg/km	Wear Rate, μm/km	Coefficient of Friction	Maximum Temperature, K
Celion 6000/Cu-Ag-P-Mg (SSC 155)	52	I	0.08	0.34	0.15	433
Celion 6000/Ag-28Cu	44	I	0.11	0.37	0.14	390
		II	0.15	0.54	0.25	413
		III	0.13	0.45	0.23	463
Celion 6000/Ag-26Cu-2Ni	30	I	0.06	0.21	0.19	433
VSA-11/Cu-Ag-P-Mg (SSC 155)	34	I	4.21	15.80	0.50	623
		II	5.61	21.00	0.36	619
		III	2.20	8.14	0.34	618
VSA-11/Ag-28Cu	37	I	0.52	1.99	0.27	552
		II	0.64	2.38	0.36	517
		III	0.54	1.99	0.41	513

[a]Orientation I = Fiber axis normal to sliding surface.
Orientation II = Fiber axis parallel to sliding surface and normal to sliding direction.
Orientation III = Fiber axis parallel to sliding surface and sliding direction.

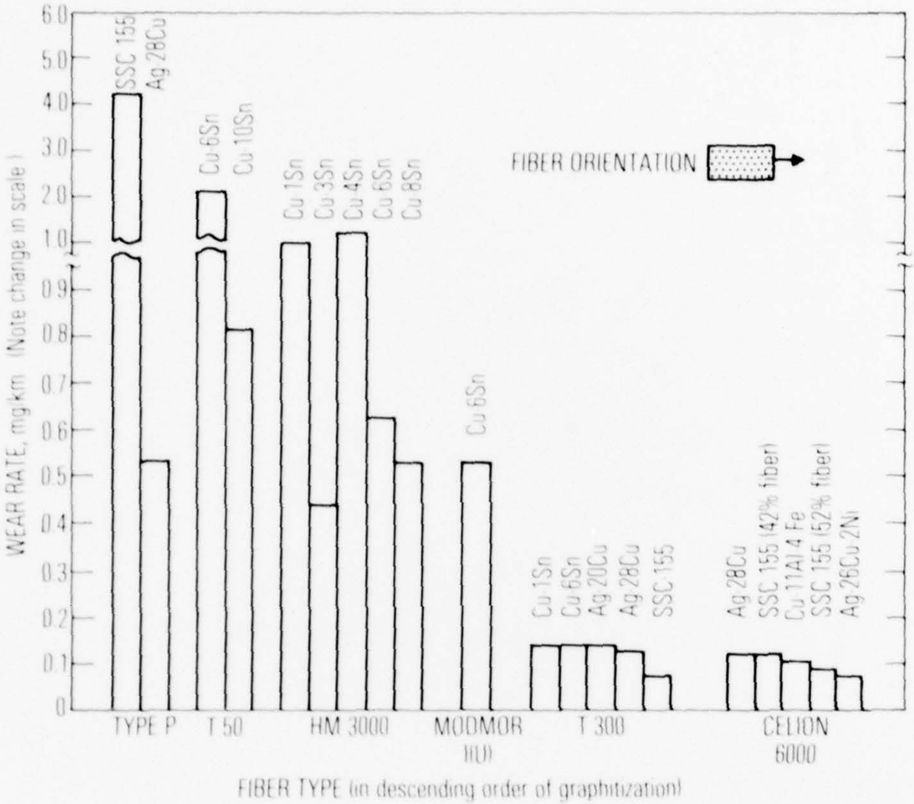


Fig. 1. Effect of Graphite Fiber Type in Wear of Various Metal Matrix Composites for Fiber Orientation I

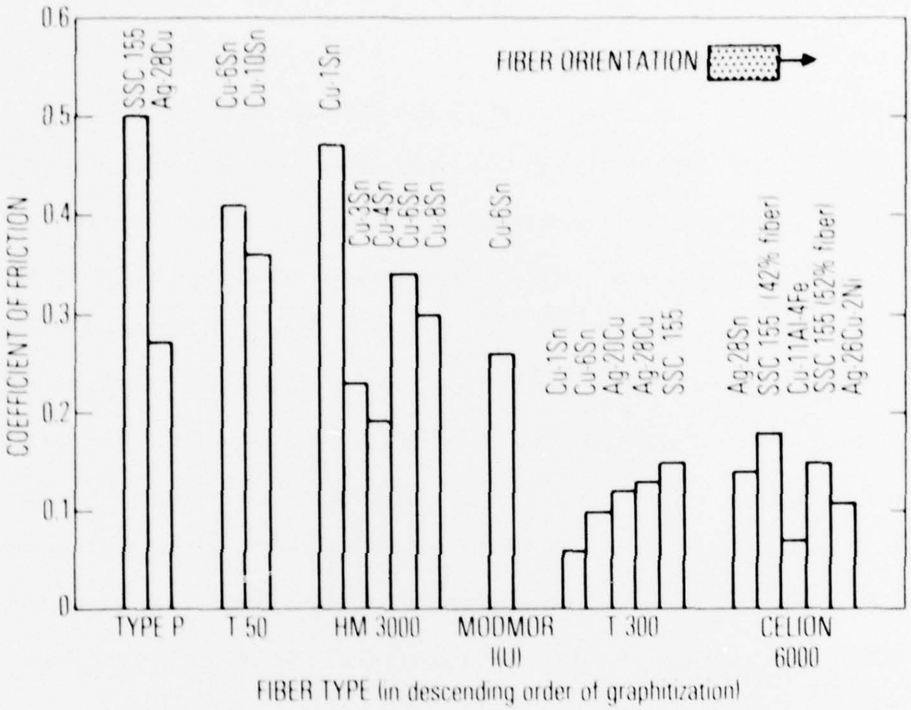


Fig. 2. Effect of Graphite Fiber Type of Friction of Various Metal Matrix Composites for Fiber Orientation I

composites; however, the difference is not as pronounced as for the wear behavior. The difference in friction for the various high-strength and high-modulus fiber composites is in contrast to the somewhat similar wear behavior. For Orientations II and III the difference in wear behavior for the high-modulus and high-strength fibers is even more pronounced, whereas the difference in friction behavior is less pronounced (Figs. 3 and 4).

The wear surface for high-strength and high-modulus fiber composites with the same matrix (SSC 155) are shown in Fig. 5. Both materials have alternating areas of smooth built-up ridges or asperities of smeared metal and plowed troughs in which fiber and debris are exposed. The origin of these alternating areas may be the machining and grinding marks on the composite and ring specimens. The difference in the trough areas of the two composites is quite striking. The fiber debris for the high-modulus pitch composite (VSA-11/SSC 155) can be over 30 μm in length, whereas that for the high-strength fiber composite (Celion 6000/SCC 155) rarely is greater than 10 μm, and usually is much smaller. X-ray analysis indicates that the areas of smeared metal consist primarily of the composite matrix metal Cu and Fe (presumably transferred from the steel mating ring). The ridge-to-trough distance in the VSA-11/SSC 155 composite appears to be greater than that for the Celion 6000/SSC 155 composite. Some iron was also found in the plowed trough areas of the Celion 6000/SSC 155 composite, but not in the VSA-11/SSC 155 composite. The mating steel surface also had alternating areas, corresponding to the composite specimens, with a layer

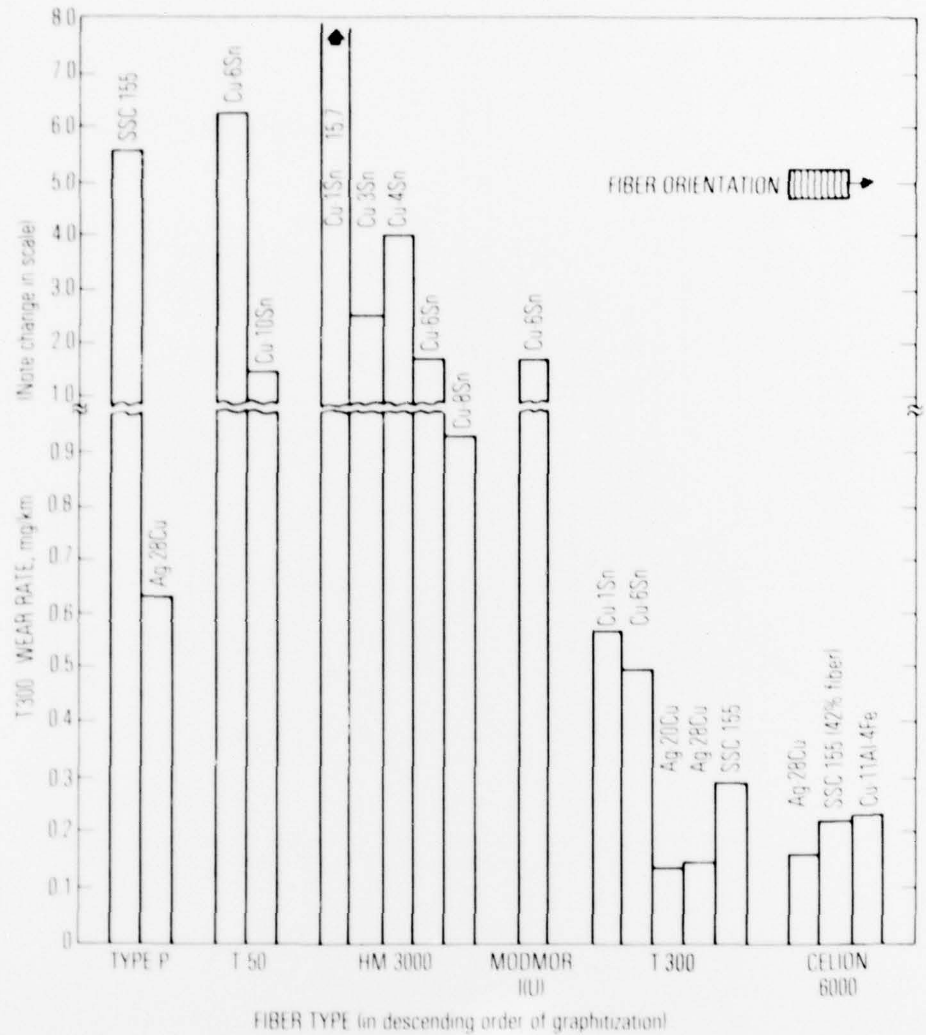


Fig. 3. Effect of Graphite Fiber Type on Wear of Various Metal Matrix Composites for Fiber Orientation II

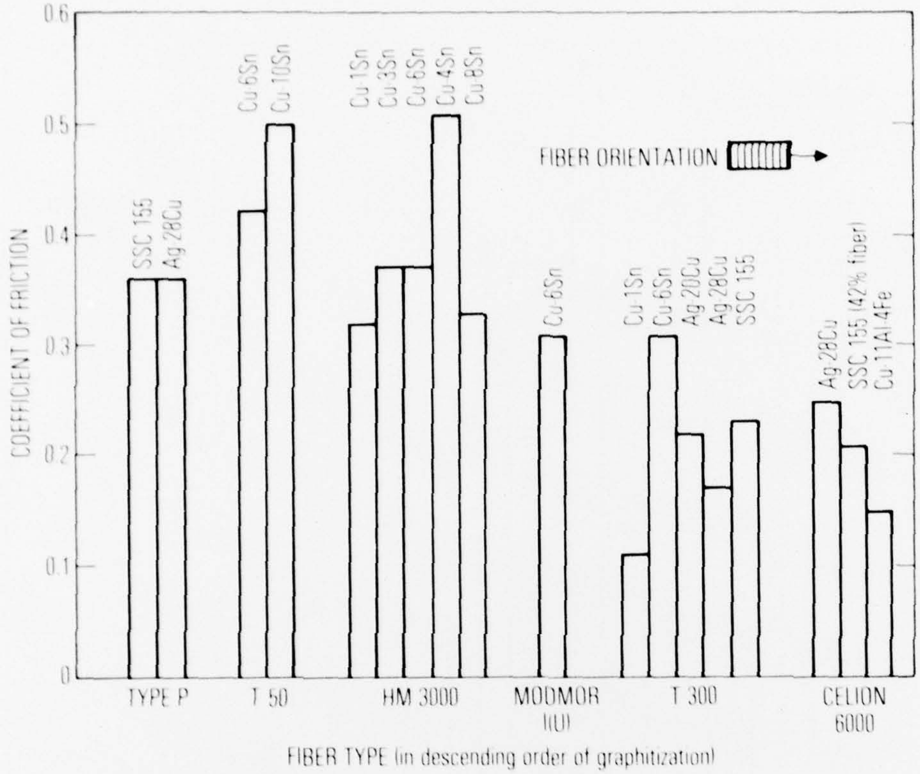
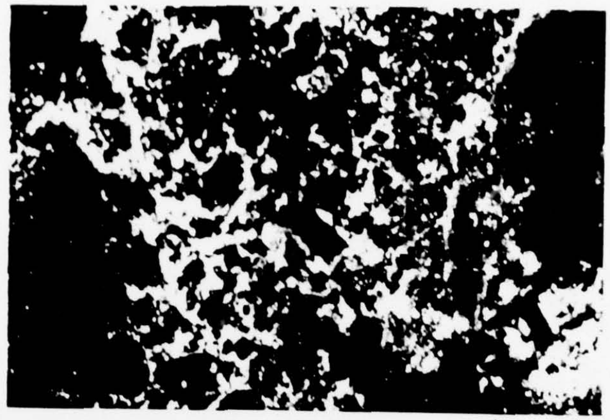


Fig. 4. Effect of Graphite Fiber Type on Friction of Various Metal Matrix Composites for Fiber Orientation II



a. HIGH STRENGTH FIBER COMPOSITE
CELION 6000/SSC 155

b. HIGH MODULUS FIBER COMPOSITE
VSA 11/SSC 155

Fig. 5. Wear Surfaces for Composites with Different Size Fibers

of Cu quite evident on the ridge area of the steel ring when run against VSA-11/SSC 155. Considerably less Cu was transferred to the steel ring when run against Celion 6000/SSC 155. These observations are summarized in a schematic representation of the wear surfaces (Fig. 6). Wear in the plowed trough area can occur by a process described in a previous paper [3]. The oxide films that are implied in that model are not shown in this representation. The high wear rate of the VSA-11/SSC 155 composite results in more material transfer to the steel mating ring than does the Celion 6000/SSC 155 composite, which is probably a consequence of the greater fiber volume in the latter composite (42% compared to 34%) than any chemical or mechanical differences in the two fibers.

The fiber fraction effects were difficult to quantify because of experimental problems associated with intentionally varying fiber content in a controlled manner. Observations on existing composites such as the HM 3000/bronze indicate that there is a trend of decreasing wear rate with increasing fiber fraction, but that there is no clear trend for the friction (Fig. 7). This conclusion must be qualified, however, because the composites with varying fiber fractions also have varying Sn content. Sn content effects may therefore be masked by fiber fraction effects.

For Orientation I no consistent correlation between alloy strength and tribological behavior could be found, although decreasing wear rate was observed with increasing Sn content (hence, increasing matrix strength) for Orientations II and III of the HM 3000/bronze composites (Fig. 8).

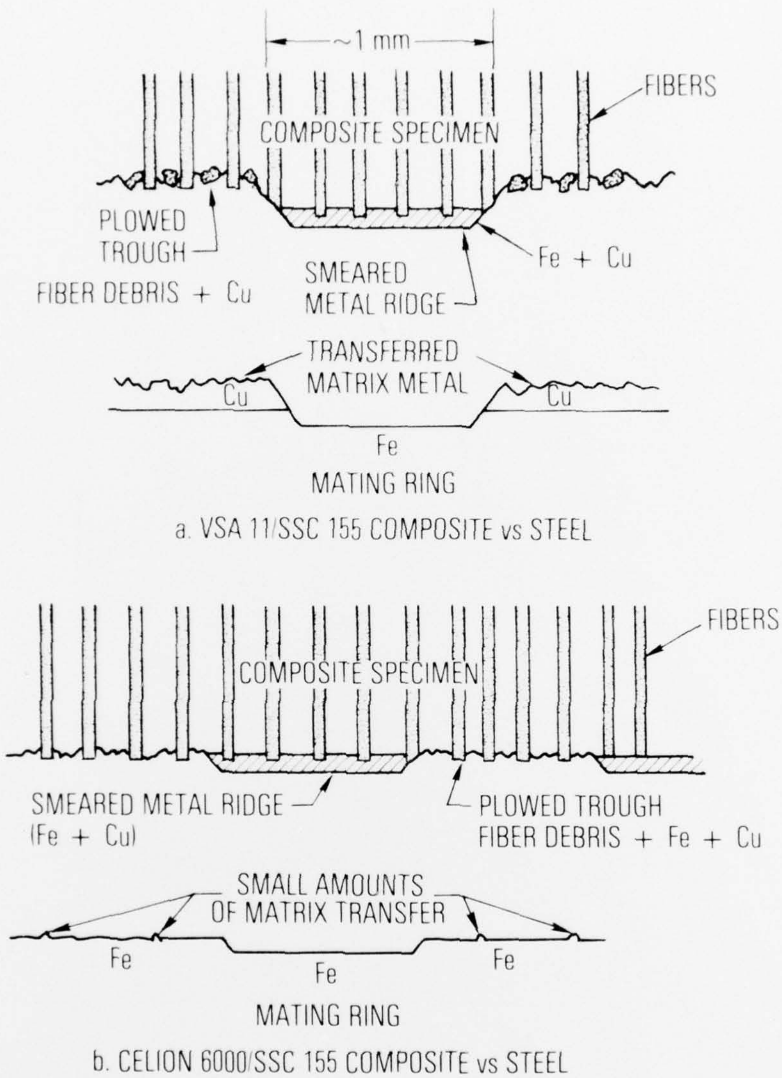


Fig. 6. Schematic Representation of Wear Surfaces for High-Modulus (VSA-11/SSC 155) and High-Strength (Celion 6000/SSC 155) Fiber Composites Against Steel

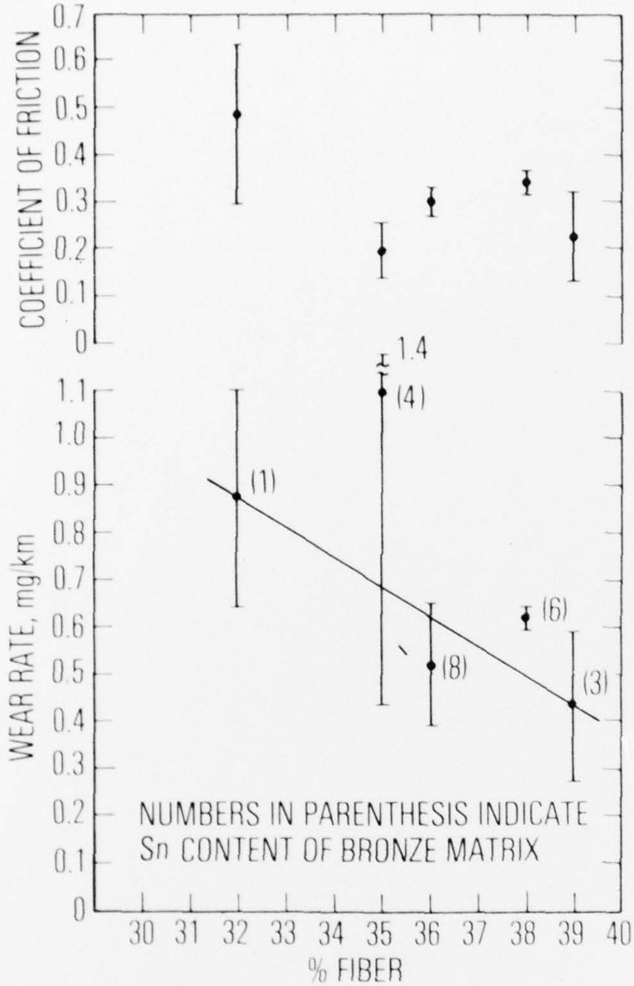


Fig. 7. Effect of Fiber Fraction on Wear and Friction of HM 3000/Bronze Composites for Fiber Orientation I

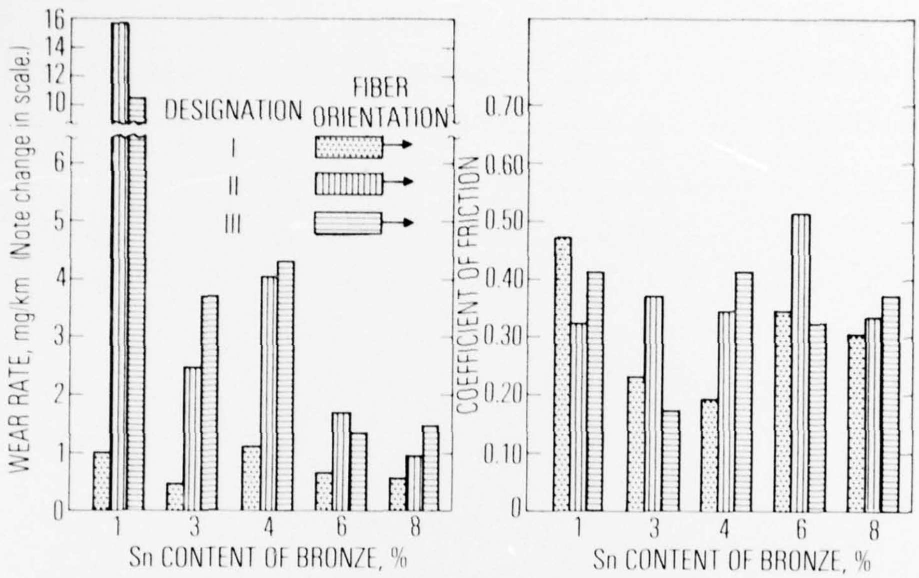


Fig. 8. Wear Rate and Friction of HM 3000/Bronze Composites for Three Fiber Orientations

The orientation effect that is so pronounced in the Cu-based and bronze composites appears to be inconsistent in the Ag matrix composites. The wear rate of pure Ag matrix composites is actually greater for Orientation I than for Orientations II and III (Fig. 9). Alloying with Cu results in similar wear properties, regardless of fiber orientations.

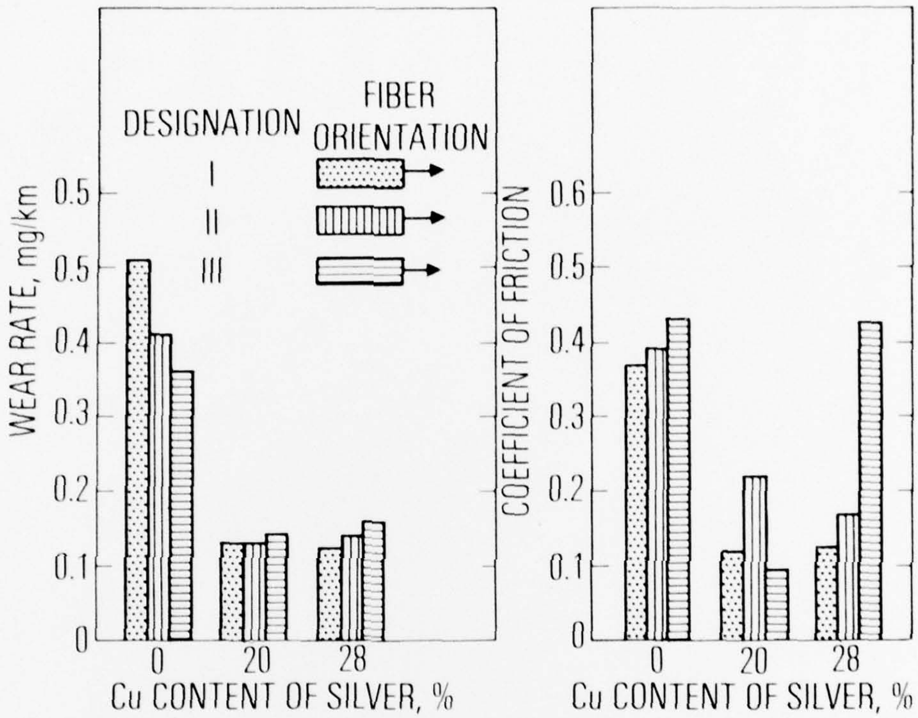


Fig. 9. Wear Rate and Friction of T 300/Ag Alloy Composites for Three Fiber Orientations

CONCLUSIONS

The type of graphite fiber in the composite is the most significant factor in the wear and friction behavior of metal matrix composites. The composites with low-modulus PAN-based fibers have the lowest wear and friction rates. The high-modulus PAN-based, rayon-based, and pitch-based fiber composites have significantly higher wear rates and friction. Fiber fraction influences wear rate, but not coefficient of friction for the high-modulus HM 3000 fiber/Sn-bronze matrix composites. The fiber fraction effect is strong enough to mask any effect of the Sn content of the matrix alloy. Neither the matrix alloy strength nor the composite strength per se correlates with the friction and wear properties; however, specific trends are evident for the various matrix alloys (e.g., Ag, Cu, and bronze) with a given class of fibers (e.g., low-modulus PAN, high-modulus PAN, and pitch). Significant fiber orientation effects found for the high-modulus rayon and PAN precursor graphite fibers were not evident for low-modulus or pitch precursor fibers in Ag alloys.

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